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NOTE

Use of satellite tags to reveal the movements of spiny dogfish *Squalus acanthias* in the western North Atlantic Ocean

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ABSTRACT: The use of popup satellite archival transmitting tags (PSAT) has helped to reveal horizontal and vertical movements of large, highly migratory fishes to assist in the management of their stocks. We tested the efficacy of a significantly smaller satellite tag, the X-tag, to track the movements of 3 spiny dogfish *Squalus acanthias* in the western North Atlantic Ocean. Tag retention rates for this study ranged between 65 and 189 d. The sharks occupied waters with temperatures ranging from 5.2 to 14.9°C and had estimated average horizontal speeds between 1.36 and 2.49 km h^{-1}. The sharks initially moved east into offshore waters after tagging in the Gulf of Maine and then into southern waters off the coast of New Jersey, USA. Diel depth patterns indicated that each shark was equally active during both day and night. Our results suggest that spiny dogfish are more mobile, both vertically and horizontally, than previously thought and that smaller PSATs can provide useful information on the movement patterns of a relatively small species of shark.

KEY WORDS: Spiny dogfish · Movement · Depth preferences · Tracking

INTRODUCTION

Until recently, most of what is known about fish movement has been derived from conventional (e.g. plastic streamer/dart) tagging studies (e.g. Kohler et al. 1998, Ortiz et al. 2003). If recovered, conventional tag data reveal only the net distance traveled and time elapsed between tagging and recovery locations (Luo et al. 2006). While this information has provided scientists with a wealth of knowledge concerning straight line movement patterns, the actual path traversed by a tagged fish, including the depths occupied, are unknown (Luo et al. 2006). The development and use of popup satellite archival transmitting tags (PSAT) is helping to reveal aspects of horizontal and vertical movements of highly migratory fishes never before realized. Furthermore, the ability of PSATs to release from its bearer and transmit archived geolocation, depth, and temperature data to researchers eliminates the need for physical recovery of the tag, thus representing a truly fishery-independent means of obtaining movement data on fishes (Luo et al. 2006). Data collected using these advanced tags are not only critical to understanding the ecology of migratory fishes but also can ultimately lead to better management of exploited stocks. The size of the first generation of PSATs precluded their use on relatively small organisms; however, they have been successfully deployed

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on large fishes such as Atlantic bluefin tuna *Thunnus thynnus* (Block et al. 2001), basking sharks *Cetorhinus maximus* (Skomal et al. 2009), salmon sharks *Lamna ditropis* (Weng et al. 2005) and white sharks *Carcharodon carcharias* (Bonfil et al. 2005).

Recently, Microwave Telemetry (Columbia, MD, USA) developed the PTT-100 archival popup X-tag. The size of the X-tag is significantly smaller than other commercially available satellite tags, thus enabling the use of advanced tagging technology to track the movements of relatively small fishes. In the northwest Atlantic Ocean, the spiny dogfish *Squalus acanthias* is considered a benthic species that has a maximum size of ~100 cm total length. This shark is distributed from Greenland to Florida but is most abundant from Nova Scotia to Cape Hatteras, North Carolina (Collette & Klein-MacPhee 2002). Limited conventional tag return data (Rulifson et al. 2002) and National Marine Fisheries Service, Northeast Fisheries Science Center (NEFSC) bottom trawl survey data (Stehlik 2007) suggest this species makes seasonal north/south migrations along the US Eastern seaboard. The current stock status of this shark within this geographic region is surrounded by uncertainty as substantial increases in the spawning stock biomass are not representative of this species' known life history characteristics (Musick 1999, Armstrong 2008). In addition, vertical movement patterns of this species remain unknown, which could potentially bias bottom trawl survey abundance estimates. Thus, the size, broad range, discrepancies in stock status and the lack of knowledge on horizontal and vertical movements of this species make it an ideal candidate for examining the efficacy of X-tags in tracking the 4-dimensional movements of small elasmobranchs. Herein we report on the first use of X-tags to investigate the movements of a shark in the western North Atlantic Ocean and describe a practical approach to analyze PSAT data using depth.

MATERIALS AND METHODS

In 2007, 3 female spiny dogfish, with a mean total length of 84 cm (SD = 4.5 cm), were fitted with X-tags at 43° 24.10' N, 70° 10.61' W on 31 October (n = 1) and 7 November (n = 2), with each tag set to release 12 mo after deployment. Tag attachment was accomplished by inserting a plastic screw through the first dorsal fin base and securing an X-tag to the screw using a 7.5 cm monofilament tether protected with flexible silicone tubing. The X-tag measured 120 × 32 mm, weighed 40 g in air and was programmed to collect light level, temperature (range –4 to +40°C; resolution = 0.17°C) and depth (range 0 to 1296 m; resolution: ±5 m) data at 15 min intervals. Once the X-tag released from a tagged shark, data were transmitted to the Argos satellite-based location and data collection system at an operating frequency of 401.650 MHz ± 36 kHz.

Initial geolocation positions produced by Microwave Telemetry, using a proprietary algorithm, were utilized in our analyses. End points of each track were assigned by choosing the first day at liberty where the depth of the shark was consistently near the surface water. To assess horizontal movements, geolocation data were fitted with a state space extended Kalman filter model (kftrack 0.70 or ukfsst 0.30) using the R statistical language (R-Core Development 2008).

For Shark 78183, 17 January was selected as the termination date based on depth records. The kftrack model was fitted to the entire track maintaining all default parameter settings (see kftrack documentation). Archived depth data were used to further constrain the geolocation estimates (e.g. Hoolihan & Luo 2007, Teo et al. 2007, Galuardi et al. 2010). In the present study, we utilized depth correction as a secondary step to state space estimation (Galuardi et al. 2010).

For Shark 78184, only 13 geolocation estimates were recovered from the X-tag out of 189 days at liberty. Our initial kftrack estimation for these few observations, using the parameter defaults, yielded discouraging estimates of latitude. Therefore, we re-parameterized the state space model to ignore latitude observations by setting the initial observation error arbitrarily high and not estimating the parameter further. There were few depth or temperature data recovered from this X-tag so no further correction could be undertaken.

Shark 78185 spent extended periods of time at depths <200 m, which resulted in a complete lack of light data. However, the X-tag obtained a nearly complete temperature and depth record. To make use of as much information as possible in estimating location, we first used ukfsst (Lam et al. 2008) and a bathymetric correction. To use ukfsst, we first built a linear geographic interpretation between the tagging and pop-off locations (GPS and ARGOS derived respectively) as an uninformative prior track (Fig. 1A) and a Reynolds 1° optimally interpolated sea surface temperature (SST) (NASA Physical Oceanography DAAC). We then set initial parameter estimates for longitudinal and latitudinal observation error arbitrarily high and switched off their estimation as well as diffusion and bias. Since the Kalman filter model is a convolution of observation and true (unknown) states, these steps have the effect of using only the random walk model and temperature records (daily maximum) from the tag as location estimators (Fig. 1B). To account for maximum daily temperatures obtained on days where minimum depth was well below the surface, we set initial SST observation error at 2°C. Finally, we applied the aforementioned bathymetric correction to the ukfsst estimated track

(Fig. 1C). Examination of the depth records indicated that the tag detached prematurely on 15 January 2008 (Day 65) and floated until it reported on 31 January 2008 (Day 82). We therefore truncated the interpretation in the previous steps to Day 65 (Fig. 1C).

The average horizontal speed using the constructed track was calculated from the most probable locations based on the filtered geolocation estimates for each day. These distances were then averaged over the length of the tag deployment to provide the average distance travelled per day. The straight line distance measurement was calculated from the start latitude and longitude (tagging location) and the stop (pop off) latitude and longitude. Temperature data were treated in aggregate to assess the range of occupied temperatures.

RESULTS

Shark 78183

Out of the 82 d at liberty, 41 had geolocations suitable for analysis. Depth data indicated that the tag popped off on 17 January 2008 although it did not transmit until 2 February 2008. During the 82 d at liberty, the shark spent the majority of time in waters <50 m (Fig. 2A) and occupied a maximum depth of 70 m. The mean recorded depths for light and dark periods were approximately equal (mean ± SD, day: 21 ± 10 m; night: 20 ± 11 m). The shark displayed an active vertical movement pattern with maximum recorded depths occurring during light and dark hours (Fig. 3). Analysis of 4379 temperature readings indicated that the shark remained within a relatively narrow range of 6.79 to 10.42°C (mean: 9.18 ± 0.52°C). The final estimated track revealed that the shark moved east after being tagged, stayed offshore during the months of November and December, and then moved in a southerly direction in January (Fig. 4A). The estimated average horizontal speed of the shark was 1.36 km h^{-1} with a total straight line distance of 459 km traveled.

Shark 78184

During its 189 d at liberty this shark occupied depths between 5 and 210 m (Fig. 2B). The mean day and night depths occupied by this shark were 79 (SD = 47) and 73 m (SD = 39), respectively. Maximum depths occupied were, with one exception, recorded during daylight hours; however, most depth records were <130 m (Figs. 2B & 3B). Analysis of the 1632 temperature readings indicated that this shark occupied waters

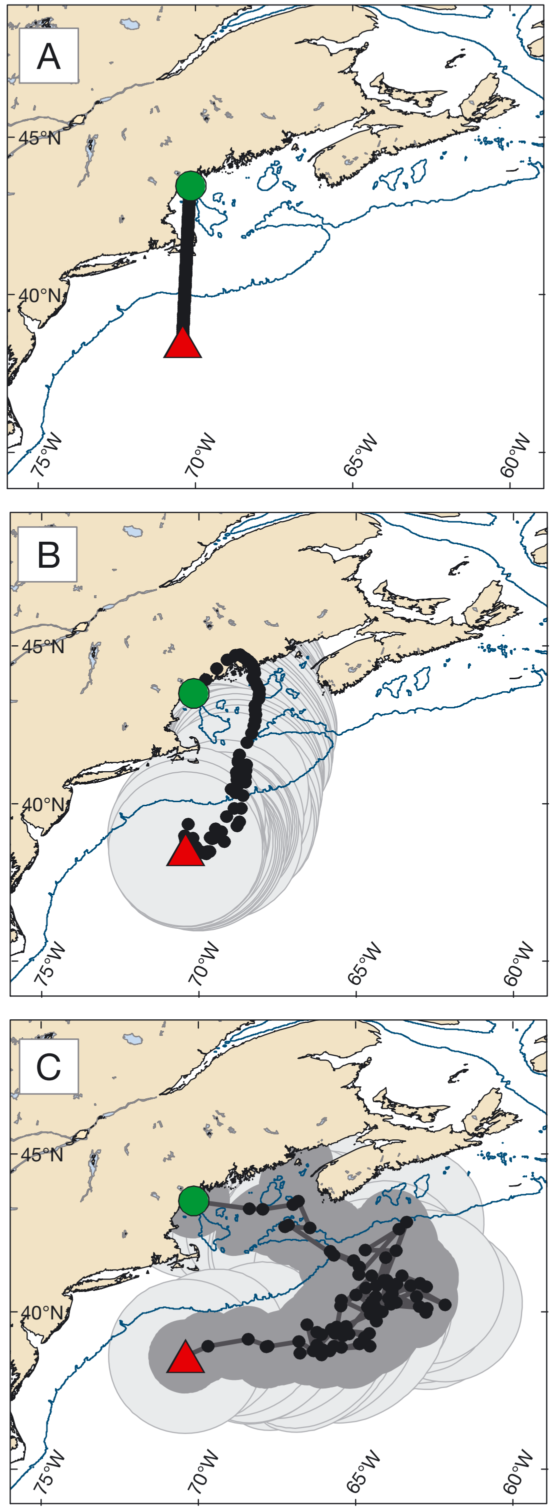

Fig. 1. *Squalus acanthias.* Schematic of geolocation steps for Shark 78185. (A) Linear, uninformative prior track between the start point (green circle) and report location (red triangle). (B) ukfsst results using only the random walk model and tag measured temperature as estimators. (C) Bathymetric correction applied. Dark grey areas: 50 % probability interval. Light grey areas: 95 % probability contour. Blue line: 200 m contour

with temperatures ranging between 5.3 and 14.9°C (mean: 8.6 ± 2.0°C). Because only 13 days worth of geolocation data were available out of the 189 d at liberty, confidence intervals for position estimates were as large as 8° latitudinally. Given our data poor constraint, this was not unexpected. Since our first model achieved local minimization (general criteria for success, kftrack, 2008) using parameter defaults, we felt the large variance in final position estimates were acceptable for large scale movements (Fig. 4B). On a large scale, the net movement of the shark was southward over its time at liberty. Horizontal speed of this shark was not calculated due to the limited amount of geolocation data. The total straight line distance traveled was 620 km.

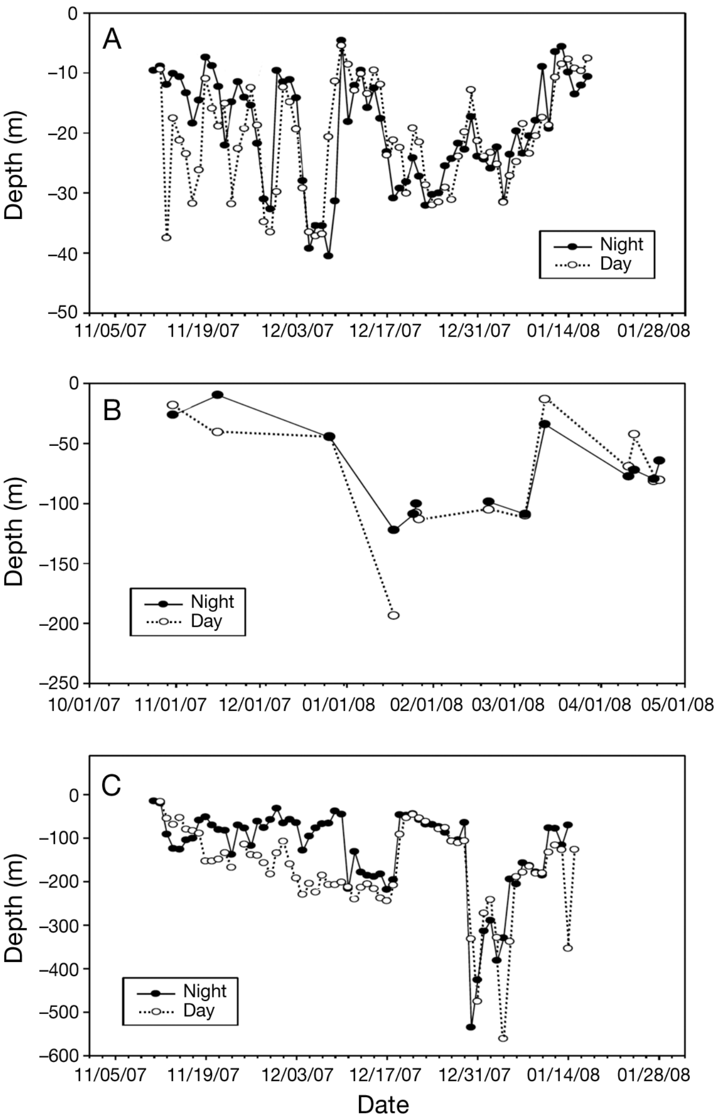

Fig. 2. *Squalus acanthias.* Diel depths (m) for Sharks (A) 78183, (B) 78184 and (C) 78185 tagged with X-tag pop off satellite tags. Date: mm/dd/yy

Shark 78185

Shark 78185 occupied the deepest depths of the 3 tagged spiny dogfish, diving to depths of >600 m on several occasions over the 65 d at liberty; however, the majority of depth records were <230 m (Fig. 2C). Shark

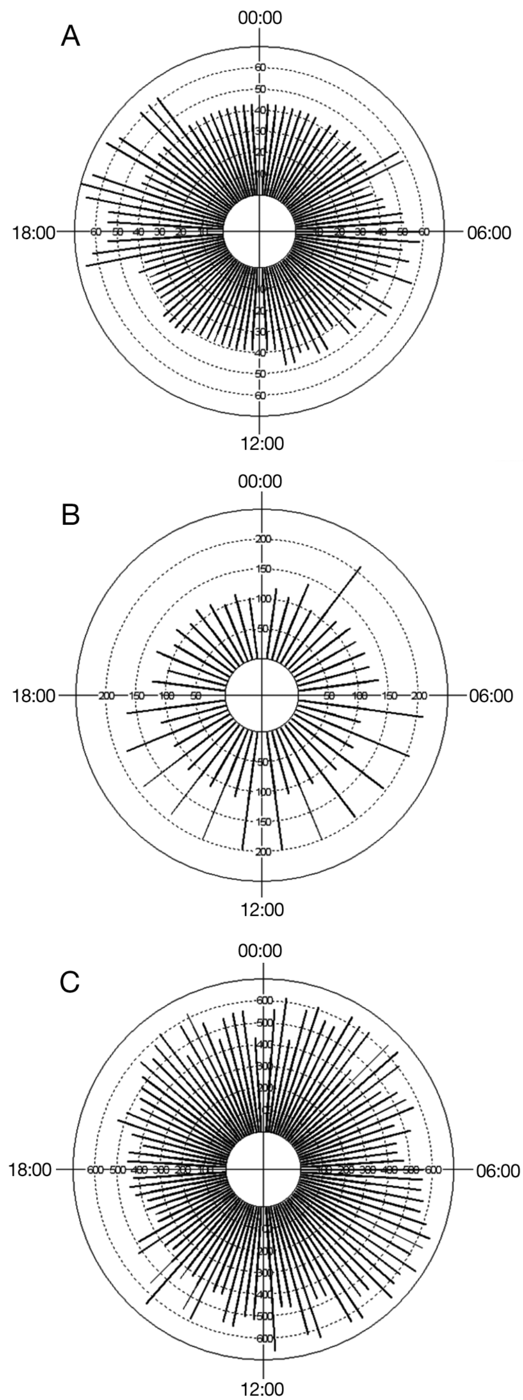

Fig. 3. *Squalus acanthias.* Maximum recorded depths for each time interval (h) for Sharks (A) 78183, (B) 78184 and (C) 78185. Inner circular axes = depth (m)

78185 displayed a highly active vertical movement pattern, similar to the other sharks (Fig. 2), with a mean daytime depth of 176 m (SD = 108) and a mean night-time depth of 129 m (SD = 110; Fig. 2C). Depths >230 m were recorded during all time intervals (Fig. 3). Analysis of 3310 temperature readings indicated that this shark occupied waters between 5.2 and 14.9°C (mean: 8.6 ± 2.0°C). The fact that this shark was rarely in waters shallower than 11 m likely played a significant role in the lack of light based geolocation measurements. This made track estimation more difficult, but the presence of temperature and depth records allowed auxiliary correction (e.g. Teo et al. 2004, Royer et al. 2005, Nielsen et al. 2006). Utilizing a non-informative linear track, temperature, and depth achieved reasonable results for large scale movement estimation. The final estimated track suggests that this shark displayed an offshore movement pattern during the months of November and December, before heading southwest in January (Fig. 4C).

The estimated geolocation track had a large variance, especially when the fish's depth was deep, lending to maximum temperatures being recorded well below the surface and the undersea topography being uniform beyond the shelf break. Based on these limitations, the data suggest that the shark was mostly beyond the 200 m contour and most likely southeast of George's Bank north of the Gulf Stream during its time at liberty. The estimated average horizontal speed of the shark was 2.78 km h^{-1} with a total straight line distance of 434 km traveled.

DISCUSSION

The present study provides new vertical and horizontal movement information for *Squalus acanthias* in the western North Atlantic Ocean and shows the applicability of the X-tag for use on small elasmobranchs. We used 3 variations of a state space Kalman filter model and auxiliary temperature and depth data to produce the first fisheries independent estimates of movement patterns of spiny dogfish in the northwest Atlantic Ocean. Although the data returned from the 3 spiny dogfish presented several challenges, the generated tracks provide sufficient information to present an overall and consistent trend in the horizontal movement patterns of this species. All 3 sharks appeared to move east into offshore waters after tagging, with 2 moving into southern waters off the coast of New Jersey, USA. This is in contrast to studies by Moore (1998) and Rulifson et al. (2002), who suggest that this species typically exhibits an inshore movement pattern. Diel depth patterns were interesting in that each shark appeared to be equally active vertically during both the day and

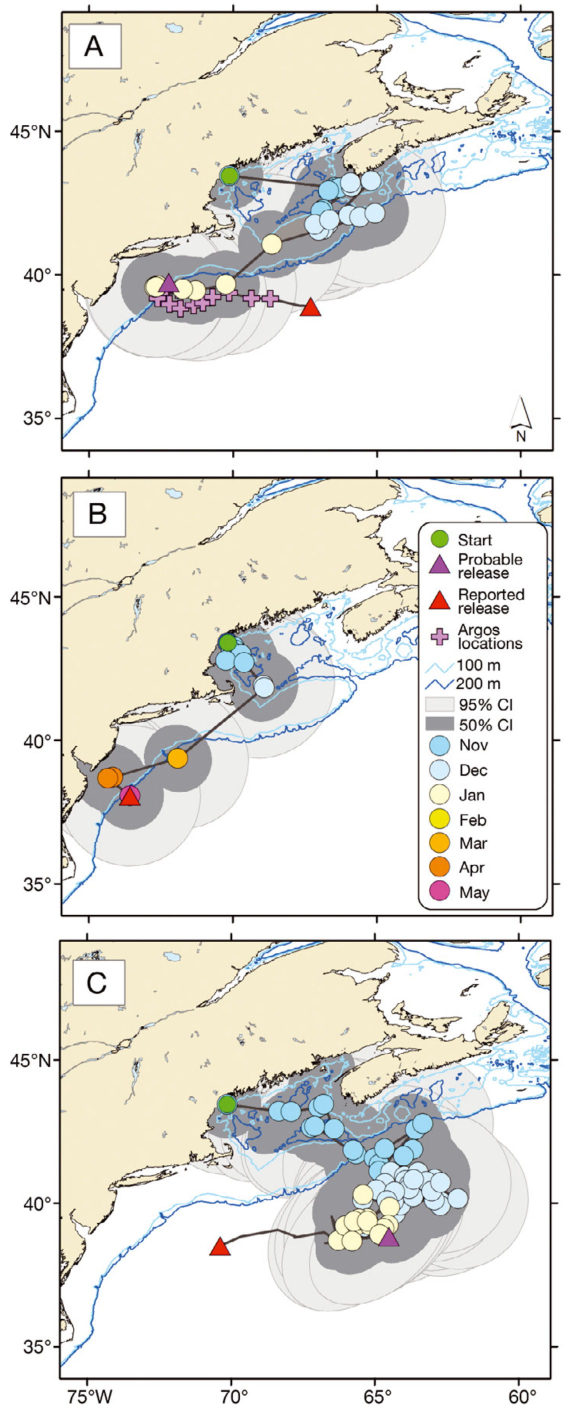

Fig. 4. *Squalus acanthias.* Final estimated tracks of Sharks (A) 78183, (B) 78184 and (C) 78185 tagged off the coast of northern New England with X-tag pop off satellite tags in November 2007. Specimens were at liberty for 82, 189 and 65 d, respectively. Tracks represent 3 geolocation procedures: track 78183 was estimated using a Kalman filter and secondary bathymetric correction, track 78184 used a Kalman filter ignoring the observed latitude and track 78185 was estimated using only temperature and a bathymetric constraint (see text for more details). Grey areas: 50 and 95 % confidence intervals (CI) for position estimates

night: a pattern suggested by Rago et al. (1998) and Stehlik (2007) but until now never documented. Another interesting component of the depth data is the broad differences in depth profiles exhibited by each shark over the course of their estimated horizontal movement patterns. While each shark moved in the same general horizontal pattern, the depths each occupied during this movement varied considerably. In summary, it would appear that the smaller X-tag can provide useful information on the movement patterns of relatively small species of sharks and that filtering techniques provided herein will potentially allow for the analysis of data that were previously considered too data poor for geolocation estimates.

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